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By G. Fischer

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TESTS OF LEAD-BRONZE BEARINGS IN THE DVL BEARING-TESTING MACHINE*

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SUMMARY

The lead-bronze bearings tested in the DVL bearing-testing machine have proven themselves very sensitive to load changes as in comparison with bearings of light metal. In order to prevent surface injuries and consequently running interruptions, the increase of the load has to be made in small steps with sufficient run-in time between steps. The absence of lead in the running surface, impurities in the alloy (especially iron) and surface irregularities (pores) decreases the load-carrying capacity of the bearing to two or three times that of the static load.

At the expiration of the 100-hour endurance run ($p = 250\ kg/cm^2$) only two alloys with favorable lead distribution and low amount of impurities showed themselves to be in perfect running condition. Practically all other bearings were ruined by the formation of deep scorings and cavities. Heavy scar formations are especially noticeable on bearings with typical dendritical grain structure. Premature forming of scars is caused chiefly by shrinkage and quenching which will create internal stresses within the lead-bronze layer.

The duration of the run-out time after the discontinuance of the lubrication up to the time of the functioning of the automatic stop of the machine, varies, according to several tests from several seconds to a few minutes. Short run-out times were noticed in all first "dry runs" in which temperatures necessary to operate the cutting out of the test machine were reached before a sufficient quantity of lead was melted.

*"Untersuchung von Bleibronze-Ausgüssen in der DVL-Lagerprüfmaschine." Luftfahrtforschung, vol. 16, no. 7, July 20, 1939, pp. 370-383.

Tests have been made on 12 lead-bronze alloys, supplied by five manufacturers, with lead content of between 1 and 24 percent on running characteristics with hardened and tempered shaft ends on the DVL bearing-testing machine.

I. INTRODUCTION

Lead-bronze bearing materials have, in spite of serious faults, held their own as materials for high-performance aircraft main bearings. To overcome lack of distribution, porosity, and inclusions, complicated melting and casting methods are needed. The difficulties are, up to today, not entirely solved and are subject to broad metallurgical study (reference 1). Furthermore, in the last few years a multitude of light-metal bearing materials have been developed with which no satisfactory performance has been accomplished in practical use under maximum thermal or mechanical conditions. As long as the question of materials for high-performance bearings is not entirely solved, an effort should be made to improve the manufacturing conditions for lead-bronze materials.

The following studies, which have been conducted on the DVL bearing-testing machine with special reference to existing pressure conditions of aircraft-engine main bearings, give additional information to the question of the load factor of lead-bronze bonds and give suggestions for further development of these bearing materials.

II. TESTED BEARING MATERIALS

For the tests, lead-bronze forms of different origin and with lead content of 20 and 40 percent were provided. Table I contains the list of the tested lead-bronze materials with details of their chemical analysis and their degree of hardness. The hardness test was made on samples of the prefabricated bearings which had a bond thickness of between 1 and 1-1/2 mm. Bearings made of alloy 20 V and 40 V were not available for hardness test in the delivery stage. Figures 3 to 15 show lead distribution of the cast parts in ground sections parallel to the bearing axis.

The influence of the lead content on the hardness of the material cast into the bearing cannot be immediately obtained from data of table I. However, in figure 1, a decrease of hardness with increasing lead content can be recognized in spite of the greatly scattered values. It is significant that the upper limits were found to have a greater, the lower mostly a smaller content of Sn + Sb + Remainder. (See table I.) Also, the lead-bronze alloys tested by Hensel and Tichvinsky (reference 2) show in figure 2 a clear increase of hardness with increase of component elements outside of lead and copper. These few impurities, therefore, must contain strong hardening characteristics. Nickel, according to Wecker and Nipper (reference 3) influences hardness only in combination with Sn and Mn. It should also be noticed that the hardness is affected by the cooling conditions after casting. The above authors determined a Brinell hardness of 44 kg/mm² for sand castings and 51 kg/mm² for form castings with a lead-bronze alloy of practically the chemical analysis (75.5 Cu, 17.5 Pb, 3.5 Sn, 3.5 Sb) Corresponding hardening differences can be noticed in figure 2. Otherwise, the scattering of the hardness values in figures 1 and 2 are due to irregularities in the lead distribution. As given in table I, the hardness of the castings tested at 150° C is between 3.8 and 8.5 Brinell (corresponding to 11 to 27 percent) lower than at room temperature.

Based on the existing test and experience, high-performing lead-bronze bearings should show a uniform lead distribution with fine globular grain of the inclusions. As illustrated in figures 3 to 15 (showing only 40 mm long etched cuts of the materials), this condition is present only in the castings of low lead content as 20 I to 20 IV. Still, these illustrations do not show the regular or fine-globular, or the fine dendritical characteristics, of the foreign bronze-lead alloys shown in figures 16 and 17. All other castings rich in lead show more or less large zones of inclusions or concentration of lead. Alloys 30 I, II, and IV, also 40 II and IV show particularly strong inclusions which can be noticed even with the naked eye on the running surface of the bearing. (See figs. 18 and 19.) A relationship of lead distribution to impurities and the contents of inclusions (nickel), respectively, is unimportant. It seems, therefore, that changes in grain are due mostly to different castings and cooling conditions. Even with different alloys from the same source, great variation of grain structures can be noticed. However, the manufacture of castings with a low lead content seems to give fewer difficulties.

The bonding between bearing material and steel shell existed without exception over the whole length of the cut. Only in alloys of group I a concentration of lead could be observed occasionally near the binding zone.

Several of the delivered bearing shells showing porosity and lead concentration were marked even by the manufacturer as rejected. It is, therefore, to be assumed that all other shells passed the inspection of the manufacturing plants. To show the influence of imperfect bearings on bearing condition, #522 - alloy 20 V, #531 - 30 V, #341 and #342 - 40 II, and #541 and #542 - 40 V, were selected.

The above described lead-bronze bearings were tested in conjunction with hardened and tempered, case-hardened and nitrided shaft ends which have already been described in reference 4. The hardness limits of different shaft ends appear again in the following table.

Identification of material	Surface condition	Vickers number (20 kg load)
VCMo 140	Treated (V)	323 to 327
D 22 S	"	363 to 373
EFD 67 G	Case-hardened (E)	675 to 714
EC Mo 80	" "	687 to 755
EFKM 54	Nitrided (N)	777 to 791
N 54 G	"	846

III. TEST CONDITION AND PROCEDURE

The paper mentioned below (reference 4) describes at length the test conditions for the experiments on the DVL bearing-testing machine, so that this does not need to be repeated.

In regard to the general trend of bearing development in the aircraft industry, these tests were conducted not only under dynamic pressure conditions, but also under static load with rotating bearing and stationary shaft end.

Starting with the existing normal and extraordinary high-load factors, the following outline of tests was followed:

a) Finding of maximum limits of lead-bronze bearings.

b) Testing of running conditions during endurance test.

c) Determination of the emergency characteristics after interrupting of the oil flow.

For the examination of light-metal bearings (reference 4) during endurance tests, a mean bearing pressure of 400 kg/cm² was selected. This was reduced to 250 kg/cm² for lead-bronze bearings during endurance tests in this case. This figure is frequently selected for airplane-engine main bearings.

The thickness of the bearing surface, which was machined with a diamond tool, was approximately 0.5 mm, the diameter 60 mm, the width of the running surface 25 mm. With these dimensions and an upper pressure limit of the test machine of 7,500 kg, a mean surface pressure of 500 kg/cm² could be reached. All other test conditions were equal to the light metal bearing experiments.

Bearing play:	1 percent (0.06 mm).
Speed:	5 m/s (n = 1,600 rpm).
Temperature:	120° C, measured near running surface.
Lubrication:	Preheated oil (90° - 100 C°) "Stanavo 120" which was filtered through felt and was injected on the low pressure side of the bearing at 4 to 5 atü (atm abs).

IV. TEST RESULTS

a) Bearing Limits under Static and Dynamic Load

To find the load limit after approximately two hours running time, the bearing pressure was increased 100 kg/cm² each time, in some cases only 50 kg/cm². The load increase from step to step should have been made within 1 to 2 minutes to conform with earlier experiments, but to prevent the automatic release of the machine during the higher load factors, a longer time interval was necessary as a large increase of energy results through disturbing the running condition.

The bearings were all given a short examination as to the condition of the running surface. Only porosity and lead segregation could be noticed which influenced more or less the running condition, dependeing on size and number. In table II, the running-surface failures and injuries before and after the test have been tabulated and marked with appraisal figures. The figures 18 to 28 of bearing surfaces should serve as explanations of these data. As is shown in table III, the greater part of the tested bearings were not in satisfactory condition. Surface made of alloy 30 I, II, IV, and 40 I, II, contained numerous small and large lead segregations. Compare figures 18 and 19 and also the corresponding microphotograph figures, 7, 8, 9, 11, and 12. The bearings 531, 541, and 542 of alloy 30 V and 40 V, which show great porosity, were included in the test only to show the influence of this defect.

The lead-bronze bearings appear in contrast with earlier light metal tests to be very sensitive to different loads, particularly under static load. In many cases, a fast increase of power and bearing temperature could be noticed even at the beginning of the load test. In the case of disturbances of this kind, the load-speed had to be reduced to prevent the automatic stop of the test machine from functioning, which would cause the destruction of the bearing surfaces. In the case of bearing 1231 of alloy 20 III, the bearing pressure of 200 kg/cm² could be reached only after 5 minutes. To increase this to 210 kg/cm² took an additional 60 minutes, so that a further increase of pressure was out of the question. From the diagrams, 29 and 30, in which the run-in time is shown in comparison with bearing pressure on a few examples, it can be seen that the run-in time depends mostly on the lubricating conditions. These again are dependent on the type of load and the condition of bearing surface. The run-in time increases very quickly on the rejected bearings (944, 331, and 322) above 100 or 200 kg/cm² as is shown in diagram 29. This run-in time is finished between 200 and 230 kg/cm² and further increase was impossible due to bearing surface conditions which prevented further normal lubrication. However, in the case of perfect bearing surface (#821), the run-in process could be extended to 460 kg/cm², but even then the run-in times over 200 kg/cm took considerable time. Very much better conditions exist under dynamic load tests (fig. 30). There, only above 300 and 400 kg/cm² can a strong increase in run-in time on defective bearings (#331, #332, #944) be noticed. On bearings with perfect surfaces, the run-in process was not finished at 500 kg/cm. This being the highest permissible pressure of the machine, it should, however, be noted that these same bearings had been tested under a static load of 200 or 460 kg/cm². However, the test of bearing 942 showed that similar conditions exist if the bearing had no previous run-in time under static load. The described results clearly indicate that the process or run-in lead-bronze bearings has to be carefully watched in service runs. Under generally static load (e.g., the main crankshaft bearing in a radial-type engine) it should be permitted to raise the load only in small steps giving a long enough run-in time between load changes. This is necessary to prevent the injury of the bearing surface through dry running.

The tabulated values for load limits in table III show that under dynamic loads the lubricating conditions are far more advantageous than with a static condition. In the first case, the load factor is in all circumstances two to three times as high as in bearings with static load. A relationship between load limit and the mean Pb content of the alloy cannot be established and can hardly be expected, because of the irregularities of the lead distribution. To draw a correct conclusion of this influence, only the percentage of lead which is present in the running surface should be considered. These observations will be further discussed in the chapter covering the influence of impurities.

Of great influence on the results of bearing runs are the pores and lead segregations which were noticeable before the test, in the machined running surface. These two faults are equally responsible for the decrease of the load factor, since, in place of the visible lead segregations, "idling pores" appear very quickly, which will more or less create lubricating disturbances. The removal of the visible lead parts does not occur through chemical influence, as, after a 30-hour test of a lead-bronze bearing in oil at 160° C, no visible signs of lead dissolving could be noticed. It is, therefore, assumed that the lead segregations are mechanically removed through the impurities of the oil. Because of an eddy effect, the slowly formed cavities are more and more enlarged until finally even the base material is attacked on the border of the pores. Figures 31 and 32 show craterlike expansions of pores which have been created in the above manner. How strongly the load faculties of a bearing are influenced through lubricating disturbances caused by pores can be seen especially in the test results of bearing 332 which showed large pores only on one half of the bearing. (See also fig. 30.) Arranging these pores into the load zone, the maximum load was found after long running time under dynamic load to be 440 kg/cm^2. After turning the bearing for 180°, a maximum load of 500 kg/cm could be reached very quickly, so that in this case the actual load limit could be estimated to be substantially higher.

Aside from the limitation of quality mentioned, the load limits are independent of the material, or the hardness of the shaft end. This is proved sufficiently by the results of bearing test 933, 934, 936; 331, 332; and 944 and 945. The values found under static load coincide well in comparable cases, in contrast to tests with dynamic loads where even by the use of the same shaft and great variations in the load factor of similar bearings exist. These irregularities are created by the unequal distribution of the lubricant. During dynamic tests can be observed, in such cases, a badly damaged as well as a less faulty bearing shell near the narrow maximum load limit, so that the above-mentioned condition for bearing 332 occurs. Under static load, however, similar differences cannot be expected for like bearings, since all irregularities in the bearing surface are sooner or later in contact with the load zone of the bearing.

The values of maximum load factors obtained from bearing 1221, 821 and 936, 831 disclose that shells with approximately the same Pb content but received from different sources, differ greatly in running characteristics under the same test condition. It seems natural to blame these irregularities on different amounts of impurities whose influence on the mechanical characteristics has already been disclosed in paragraph II. In figure 33 the dependence of the load limit on the content of inclusions (Sn + Sb + Remainder) in the bonding material is graphically illustrated. The two lines which only connect similar test results show clearly a decrease in maximum load pressure with increasing inclusions. It can therefore be considered that since the hardness of the bearing material depends on the amount of impurities there can be no relationship between hardness and maximum load factor. It can be assumed, however, that the forming of "Beilby layers" (reference 5) and therewith the adhesion of the lubricant will be reduced through the presence of certain impurities. Figure 33 does not include values of bearings 842 and 847 made from alloy 40 IV, as they are far below the load limits illustrated. It should be mentioned that these alloys contain 0.28 percent Fe, which is a very high iron content in comparison with all other lead-bronze bearing mixtures. Since in this case the amount of iron is almost equal to the whole amount of inclusions, it should be concluded that iron has a specially strong influence for reducing the load factor of lead-bronze bearings.

Figure 33 also discloses that the load factor of bearings of the same origin is lowered correspondingly to the valuation figures which had been assumed according to the condition of the bearing surface before the test.

In consideration of these factors, it can be noticed after closer examination that a dependence of load limit on lead content, or the lead amount in the bearing surface, exists. The upper line in figure 33 takes into account the test results 0/IV, 0/V, 0/I, and 0/III bearings with perfect surface (valuation figure, 0). The bearing shells in question show a grain with rather uniform lead distribution (see figs. 3, 4, 5, and 10) so that the mean lead contents given in table I correspond approximately to the lead content of the running surface. It can be concluded from figure 33 that the maximum determined load capacity 0/V will be above the upper line of the diagram for bearing shells having a rich lead mixture and below 0/IV for a small lead content. However, the values 0/I and 0/III situated on the line have bearing shells of almost equal Pb content (21.7 and 22.6 percent Pb). It can therefore be assumed that the maximum loadability increases with an increasing lead content. Bearings from alloy 20 V and 40 V show a very low amount of lead in the microphotographs 6 and 15 and had also a relatively low load limit. One more proof of the assumption of the influence of lead content is given by means of a test with a bearing entirely free of lead (film of electrolytic copper of 1/2 mm). This bearing stood up under a static load of only 180 kg/cm^2. All other test results which had been conducted on shells with numerous visible lead inclusions cannot be used in the diagnosis of the influence of lead contents, since the lead inclusions in the bearing surface vary too much during the test run on account of forming of porosity which has already been described above. Finally, it should not be overlooked that, because of the numerous factors of influence, scattered test values have to be expected through small variations in test conditions (temperature, bearing tolerances, etc.) but mainly through variations in lead content as well as in the amounts and composition of the impurities can the comparison be affected essentially. It is also to be considered that the condition of the running surface cannot be definitely determined since during the run additional changes occur (scars, scratches, etc.) which will influence the maximum loadability. But it can be definitely concluded from the existing test figures that within the limits of the above tests the load-carrying capacity of lead-bronze alloys will be more or less uniformly reduced through low lead content, running surface defects, and amount of impurities.

Occasionally during the experiments with bearing 932 a strange influence of the rim pressure was noticeable on the loadability. During one-sided pressure distribution, which is stretched to approximately one-half of the width of the bearing surface (see fig. 20), a mean bearing pressure of 70 kg/cm^2 was reached, which is just about one-half the amount of the similar bearings (933, 934, and 936).

The majority of the given bearings in table III show after the test run numerous scratches in the running surface. These scars are generally already noticeable after the first run under static load. In some cases, this destruction starts only after some higher dynamic loads are applied.

Under actual working conditions, only the high-loaded bearings 821, 522, and 942 appear to have perfect running surfaces after the test. On the other hand, cracks appear on the high-capacity-bearing surface of (bearing 533) already above a surface pressure of 300 kg/cm^2. It should be observed also that bearings 944 and 945, made of the same alloy 40 I, have greatly different surface conditions in spite of an equally high load. The destruction through heavy scar formation in the last-mentioned bearing is due to the effect of dry friction, to which the bearing surface was exposed because the unloading did not occur instantaneously enough, and the bearing was subjected for a short time to an increase of load and temperature. Probably this effect is intensified by the lead deficiency in the bearing surface produced by the removal of the Pb inclusions. This example illustrates again the high load sensitivity of lead-bronze, which necessitates a careful supervision of the run-in time. In most instances slight injuries of the shaft could be observed; only the journal used with bearing 945 shows signs of wear in a few places.

The determined bearing clearance varies from a few thousandths to a few tenths of a millimeter. The greatest wear shown on the bearing 945, which had a clearance of 0.24 mm. It is generally assumed that the differences in wear are mainly affected by differences in load duration near the upper limits of capacity.

The short time permissible bearing pressure under which only bearing surface damage equal to the valuation figure 2 occur, was determined in only a few cases. Most of the tested bearing castings already contained more or less coarse defects (valuation figures, 4 to 8) before the test, so that their use as high-performing bearings was impossible. Only the bearings of alloy 20 IV (#821), alloy 20 V (#522), as well as alloy 30 V (#533), approved as in perfect condition, could show a permissible running surface after an endurance test above the permitted load pressure of 250 kg/cm². The perfect bearings 927 and 1221 made of alloy 20 I and 20 III were only partly usable on account of cracks and broken-out parts which had developed under relatively small static load. Alloy 40 I was in perfect condition (cast bearing 942 was the only one of 10 of the same alloy which was in perfect condition) during dynamic load and proved itself equal to the maximum duty of alloy 20 IV. The bearing shells of this alloy which contained a multitude of lead inclosures (bearing 944 and 945) show, however, running conditions similar to the corresponding bearings of other compositions and make.

b) State during Endurance Tests

A running time of 100 hours, at a bearing pressure of 250 kg/cm² was selected for the endurance tests. This test pressure which corresponds to the permissible rating in different aircraft-engine main bearings was set as a minimum. Only bearings of alloy 20 I, 20 IV, 20 V, 30 IV, 30 V, and 40 V could be used for endurance test under static load as the results of the load factor tests showed that bearings of alloy 20 V and 40 V were no longer available.

From all bearings tested under static load, only 823 and 535 of alloy 20 IV and 30 V proved to be in perfect running condition during the whole test. Bearings of alloy 20 I and 30 IV broke down after 80 and 24 hours, respectively, forming large cracks and rough surfaces. This condition was to be expected when it is considered how close the applied pressure (250 kg/cm^2) came to the maximum load capacity (300 kg/cm^2).

The perfect running condition of bearings of alloy 20 IV and 30 V is confirmed by similar good condition under dynamic load. Even alloy 40 I (bearing 946) stood the dynamic test without surface injury, if it is overlooked that lead inclosures and pores which should have excluded the bearing from the test were present from the beginning. The other alloys due to the formation of cracks and roughness of the running surface did not stand up under the requirements. A tendency to form cracks and roughness was noticed mainly on alloy 20 I and 30 IV (bearings 922, 832, and 833) and in a less pronounced form also on alloy 20 IV (bearing 823). Roughness of a bearing can be interpreted as the condition of closely situated or overlapping cracks.

This could be observed mostly on bearings when the journal diameter was smaller in the center portion. During the test run, apparently most of the oil impurities gathered there and the running surface was attacked most severely in this section. It is remarkable that only the above-mentioned alloys as illustrated in figures 3, 5, and 9 show a typical dendritical structure which has been generally regarded unfavorably for practical use. The assumption that dendritical structure increases the tendency for Cu parts to break out in comparison with globular Pb distribution seemed borne out by the results gathered.

The reason for the premature crack-forming of lead-bronze bearings cannot be definitely determined through these tests. It is, however, unusual to note that some bearings with visable lead inclosures and pores show no cracks after running (see bearings 946 and 342), whereas others, having perfect running surfaces in the beginning, have been practically destroyed (see bearings 924 and 1232). It seems, therefore, that the formation of cracks does not occur solely through the influence of segregations and the resulting porosity. There also is no convincing reason to assume that the destruction of the material is started through lack of binding of the material. However, it was observed that some bearings which showed a tendency to crack formation, had numerous fine cracks after being stored for approximately 2 months, although nothing could be noted even under a microscope after the final manufacturing operations. (See figs. 34 and 35.) There were also fine cracks visible after the finishing operations in cases where the bearings were heated up to 160° C. (See figs. 36 and 37.) The micrographs 38 and 39 show lead deposits within the crevices of the stored bearings which indicates that the damage occurred during the cooling process of the bearing. It could be assumed therefore that fine cracks were present from the very beginning but were noticeable only after the surface becomes smooth during the test run and the cracks enlarged through the influence of internal tension. In actual runs, the cracks will open up because of the increase in temperature, as the lead inclosures expand more than the copper base. The resulting pressure is so great that the lead is squeezed from the larger pores and cracks. (See fig. 37.) The tensions within the cast part of the bearing are due to the greater shrinkage of the lead-bronze in comparison with the steel shell and are due also to the quenching of the bearing, which is done to prevent the forming of lead inclosures. The greatest internal tensions, that is, the greatest deformation after releasing the tension through cutting the bearing lengthwise in half was noticed on bearings indicating a tendency to forming of cracks. The reduction in diameter in these cases was from 0.8 to 1.0 mm; in other cases only from 0.2 to 0.4. Finally, it should be considered that the elasticity of the lead-bronze has an influence on the formation of cracks, which is due to internal tension. This is influenced mostly by the casting conditions, the composition, and the form of crystallization. The experiments made by Hensel and Tichvinsky (reference 2) on lead-bronze materials of the same analysis (75.5 Cu, 17.5 Pb, 3.5 Sn, and 3.5 Pb) show that when the pouring temperature was increased from 1,050° to 1,150° C for die castings the elongation limit is increased from 5 to 14.3 percent; for sand castings this increase is from 11.7 to 17 percent, respectively. Other tests with lead-bronze alloys containing 11.06 to 28.06 Pb showed an increase of the limit of elongation from 1.8 to 8 percent. A relationship of these values on the lead content can apparently not be established because of the influence of the crystallization characteristics. Although temperature and analysis have been kept unchanged, scattered values for the limit of elongation from 2.5 to 7.3 percent were found. It can be concluded from the above discussion that scar-forming is introduced mainly by excessive high internal tension combined with insufficient elasticity of the material. The cracks are present in some cases in the unused bearing. In others, they are developed during slight overload periods in actual service; compare figure 40. Since it was not possible to observe any deviation of normal running condition during the 100-hour endurance test because of the formation of cracks, their possible presence causes a breaking-up of the bearing material. This constitutes a great danger which definitely must be prevented in aircraft engines. In this connection, it should be pointed out that the cracks illustrated in figure 34 could not be detected by X-ray examination. Consequently, it is reasonable to assume that similar faulty conditions could not be detected in the final inspection. Special consideration should be given to the destruction of bearings through peeling of the running surface (fig. 41, alloy 40 IV, bearing 846). At the first impression this seems to indicate a faulty binding between bearing material and shell. By the careful removal of the peeled-off layers, it was discovered that this had taken place only within the load zone of the bearing and then approximately 0.1 mm from the bonding point between bearing and shell. Apparently the thin netlike structure (fig. 14) is crushed through the constant pressure change during the endurance run. This crushing is also accentuated by the brittleness of the matieral due to its excessive iron content. In regard to the position of the fracture, it should be borne in mind that if a perfect bonding form exists, the base of the alloy resists deformation and the top layer is hardened through pressure on the running surface. The fracture therefore will occur in the layer where the sum of both actions will be at a minimum.

The bearing wear is less under dynamic than under static loading as shown in table IV. In general, however, it is not possible to make a comparison of wearing qualities of different bearings because of the great variations of running time and bearing loads. It should be mentioned, however, that bearings 535 and 536 of alloy 30 V seemed little worn in spite of their low hardness figure, which is caused by elevated pressure and temperature (14.3 kg/mm^2 and 150° C).

All journals, the heat-treated as well as the hardened ones, were still in working order after the tests and no appreciable wear could be detected. Only journal 10 V when used in bearing 922 showed a few grooves on its heat-treated surface. The actual measured wear was only 0.002 mm.

c) Condition after Stopping the Oil Supply to the Bearing

Tests simulating emergency running conditions were conducted, on bearings already tested but still in good condition, under the same load conditions as those which existed during the endurance tests. The flow of lubricant was interrupted by means of a stopcock as soon as normal running conditions were reached. In most cases, eight dry-running tests were made one after the other, and in every case a record was made of the increase of temperature and the time needed to release the cut-out of the testing machine. In earlier publications, it was pointed out that the driving motors of the test machine permit a load increase of only 50 percent. Therefore, with light metal alloys the test could not be conducted to the complete destruction of the bearing.

The running time observed was in most cases extremely short and was reached in most cases in only a few seconds after lubrication was stopped entirely. Referring to table V, the same took place with the lead-bronze alloys where the "run-out" time of a few seconds is standard performance. This condition is caused by the cutting out of the testing machine, which does not permit the temperature to rise to the point where the melting point of lead is reached during the first dry test. During the next tests, more lead was deposited on the running surface, so that finally a sufficient amount is present to act as emergency lubricant at relatively low output. Since lead escapes continuously on the sides of the bearings, the temperature rises again to the point where enough lead is present in the running surface of the bearing. During a dry-running test, a step-like rise of the temperatures can be observed when a temporary increase in driving energy releases the cut-out of the test machine. Under favorable conditions, a complete dry-run time of 10 minutes has been accomplished. In most cases, the running conditions of these bearings are little influenced by the heavy surface injuries sustained during a dry run, and it is possible after a short time to reach almost the original, normal conditions.

In contrast to the behavior of lead-bronze bearings during a dry run, an injury to the surface can take place under normal lubricating conditions without preventing the failure of the bearing through emergency lubrication at the right moment. (See bearings 831 and 922, in tables III and IV, respectively.) In these cases, the cooling influence of the oil will retard the increase of temperature enough to destroy the bearing completely in some cases through dry friction. From figure 42, it can be seen that even with lubrication of the bearing a localized lead separation may occur through a suddenly appearing surface injury. Still, this interruption caused the testing machine to release the cut-out, since because of the premature hardening of the lead a wedging effect resulted within the bearing.

Under static load, shorter dry-run times were noted in almost all cases in comparison with dynamic tests, as the lubricating conditions are less favorable. The gain in temperature increases with the length of the dry run from 5 to 80° C during running times of three seconds to 13 minutes. After a dry run, running surfaces show heavy scars, scoring, and fractures, and only a few bearings show little change over the original condition if one disregards the layers of lead. The journals were injured through scoring in only a few cases. It should be mentioned also that the bearing shells made of electrolytic copper stood up under dynamic load eight dry runs without any noticeable changes of the journal or the running surfaces. The run-out duration is, however, shorter under the same test conditions than with lead-bronze alloys. The running characteristics of electrolytic copper under normal lubrication (see results of load factor determined in table III) as well as during dry runs cannot be regarded as unsatisfactory in comparison with the test results of lead-bronze bearings.

V. CONCLUSION OF TEST RESULTS

From the tests described in paragraph IV, it can be concluded that most of the lead-bronze bearings regarded as perfect by the manufacturer are not suitable for the use in high load bearings.

It was found that the loadability of the bearing is considerably reduced through:

a) Numerous lead inclosures which can be noticed in the finished bearing surface with the naked eye.

b) Insufficient lead content in the running surface.

c) Impurities within the alloy.

Failures of the bearings during endurance runs through scores and fractures are due to:

d) Large dendritical grain form of the bearing alloy.

e) Limited elasticity.

f) Internal tension within the lead-bronze surface due to shrinkage or quenching.

The difficulties enountered in the manufacture of lead-bronze castings with steel shells are due to the following contradictory causes.

1) High pouring temperature and slow cooling to obtain a good bonding between alloy and shell. (Inadequate diffusion during high temperature.)

2) Low pouring temperatures and fast quenching to result in favorable lead distribution. (Prevention of lead segregations and coagulation.)

The current methods of manufacture of lead-bronze bearings is conducted in general after the following principle:

Contact of the hot alloy with the steel shell is maintained as long as possible. This is followed by quenching. The bearing shells manufactured in this manner show almost always excellent bonding between the surfaces. However, the qualities for a high performance bearing are not satisfactorily achieved.

Great difficulties are encountered when an effort is made to create a uniform, fine, globular lead distribution with high lead content which would give the best running results. The importance of the grain structure due to unfavorable lead distribution on the running characteristics has been illustrated already. (See under a, b, d, and e.) Although much work has been done to find a substance which will influence the grain structure of lead-copper alloys, no real progress has been made. Special attention should therefore be given to the suggestion of using a high-frequency furnace (centerless induction furnace) to melt the charge. The fine distribution of the material can be attributed to the eddies within the molten mass which probably reduces the separation process during the cooling period. In order to prevent oxidation during the high frequency melting period, careful covering and quick pouring of the charge is desirable.

Little has been observed of the influence of the inner tension due to shrinkage and quenching on the running qualities of the bearing. It is important that the life as well as the endurance of the materials is greatly reduced by these stresses. Despite good bonding and even lead distribution, a premature destruction of the bearing may occur through fractures which encourage the separation of copper particles. It is quite probable that the sudden failure of otherwise perfect bearings is caused by similar conditions. Next to good bonding and equal lead distribution, the prevention of high internal stresses is the most important demand which should be desired in a high-performance lead-bronze bearing.

Furthermore, there is the danger of impurities within the alloy, such as iron from the steel shell or impurities from the use of salvaged materials, which for economic reasons must be used over again. The above tests have shown that presence of small quantities of impurities, particularly iron, appreciably reduce the capacity of the lead-bronze bearing.

It seems logical to assume that the limitations mentioned above could be avoided or reduced if a steel shell could be fastened to a separately produced lead-bronze body (reference 6). In this case, a manufacturing procedure could be developed which would result in a pure lead-bronze bearing of the most favorable structure. On the other hand, internal stresses in the lead-bronze structure can be produced by the attachment of the bearing shell, which would increase the endurance stability of the bearing. In certain cases, the increased adhesion could be produced by introducing a binder which has a favorable diffusive quality. This type of binder might make it possible to fasten together the separately made bearing parts by means of a suitable heat treatment.

Translation by United Aircraft Corporation,
East Hartford, Conn.

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TABLE I

Composition and hardness of tested lead-bronze bearings.

Alloy	Manuf'er	Delivery date	Composition in % Pb	Cu	Ni	Sn+Sb	Remainder	Hardness H 2.5/15.625/180 Kg/mm² at 20°C	at 150 °C	Grain structure as in Fig.:
Leg. 20*)	I	Sept. 1936	21,70	77,80	Sp.	0,05	0,45	45,0	36,5	3
	III	Aug. 1937	22,58	76,70	Sp.	0,55	0,17	31,7	26,0	4
	IV	Jan. 1938	16,79	83,15	—	—	0,06	40,4	33,1	5
	V	Mai 1937	23,37	76,52	0,10	—	0,01	—	—	6
Leg. 30	I	Sept. 1936	25,60	73,50	0,08	0,13	0,69	39,6	35,3	7
	II	Juni 1937	32,34	67,34	Sp.	Sp.	0,32	31,7	23,8	8
	IV	Jan. 1938	29,70	69,22	0,80	—	0,28	26,9	21,6	9
	V	Febr. 1938	27,79	71,97	Sp.	—	0,24	19,5	14,3	10
Leg. 40	I	Sept. 1936	35,20	64,20	Sp.	0,06	0,54	36,0	32,2	11
	II	Juni 1937	36,62	63,13	Sp.	Sp.	0,25	23,5	19,7	12 u. 13
	IV	Okt. 1938	42,17	57,54	Sp.	Sp.	0,29 (0,28 Fe)	23,2	18,9	14
	V	Mai 1937	38,32	60,55	0,96	—	0,17	—	—	15

*) Leg. 20: 15 bis 25% Pb; Leg. 30: 25 bis 35% Pb; Leg. 40: 35 bis 45% Pb.

TABLE III

Results through determining the load factor.

Bearing alloy	Bearing #	Bearing valuation # before test	Journal #	Bearing tolerance in ‰	Bearing static load kg/cm²	Capacity dynamic load kg/cm²	Valuation # after test Bearing	Journal	Total running time under load	Bearing wear mm · 10⁻³		Journal wear mm · 10⁻³	Short time permissible bearing pressure kg/cm²
20 I	927	0	3 N	1,17	305	—	7 rs, 2r	1 r	9	10	11 5)	0	0
20 I	927	7 rs, 2 r	3 N	—	—	> 500	7 rs, 2r	1 r	8	2	0	1	—
20 III	1221	0	1 E	1,03	210	—	4 a, 2 r	2 r	5	13	14	1	100
20 III	1221	4 a, 2 r	1 E	—	—	400	7 rs, 4 a	2 r	9	12	7	0	—
20 IV	821	0	1 E	0,92	460	—	2 r	2 r	13	23	25	0	400
20 IV	821	2 r	1 E	—	—	> 500	2 r	2 r	7	2	2	0	500
20 V	522	1 p	16 E	1,02	395	—	1 r	1 r	40	119	121	0	350
30 I	932	6 bl	15 V	0,95	70 2)	—	7 rs, 6 p	1 r	20	9	3	2	—
30 I	933	6 bl	15 V	0,97	125	—	7 rs, 6 p	2 r	9	12	10	5	—
30 I	934	6 bl	9 N	1,48	135	—	7 rs, 6 p, 2 n	1 r	17	22	18	1	—
30 I	934	7 rs, 6 p, 2 n	9 N	—	—	300	7 rs, 6p, 3 n	1 r	8				—
30 I	936	6 bl	9 N	1,02	115	—	7 rs, 6 p	1 r	9	2	13	0	—
30 I	936	7 rs, 6 p	9 N	—	—	220	7 rs, 6 p	2 r	7	8	0	0	—
30 II	331	7 bl	2 E	0,97	230	—	7 p, 1 r	2 r	7	25	30	0	—
30 II	331	7 p, 1 r	2 E	—	—	400	7 rs, 7 p	2 r	6	16	16	1	—
30 II	332	7 bl/0 3)	14 V	0,95	200	—	7 p	2 r	14	39	41	1	—
30 II	332	7 p/0 4)	14 V	—	—	440/>500	7 p, 7 rs	3 r	9/11	21	10	1	—
30 IV	831	6 bl	16 E	1,02	300	—	6 p, 7 r	2 r	7	—	—	0	—
30 V	531	8 p	2 E	1,13	135	—	8 p, 1 r	2 r	26	111	119	0	—
30 V	533	0	2 E	1,13	470	—	7 rs, 2 r	2 r	13	10	21	0	300
30 V	533	7 rs, 2 r	2 E	—	—	> 500	7 rs, 2 r	2 r	6	0	0	1	—
40 I	942	0	14 V	0,95	—	> 550	2 r, 2 a	1 r	33	38	36	1	550
40 I	944	6 bl	4 N	1,07	200	—	5 rs, 6 p, 4 a	2 r	10	31	42	0	—
40 I	944	5 rs, 6 p, 4a	4 N	—	—	415	5 rs, 6 p, 4 a	2 r	12	36	10	0	—
40 I	945	6 bl	17 E	1,05	200	—	7 r, 6 fr	5 fr	2	240	235	0	—
40 II	341	8 bl	8 E	1,07	135	—	8 p, 7 rs	1 r	6	61	58	0	—
40 II	341	8 p, 7 rs	8 E	—	—	400	8 p, 7 rs	2 r	6	32	12	1	—
40 IV	842	6 p	10 V	0,87	170	—	7 r	2 r	2	87	87	0	—
40 IV	847	4 p	3 N	1,07	—	> 500	7 rs, 4 p	2 r	11	20	22	0	—
40 IV	847	7 rs, 4 p	3 N	—	180	—	7 rs, 4 p	2 r	5	7	6	0	—
40 V	541	7 p	1 E	1,07	135	—	7 p, 4 r	3 r	10	103	103	1	—
40 V	542	4 p	8 E	1,12	250	—	5 r, 4 p, a	3 r	22	154	156	0	—
Electrolytic copper	10	0	4 N	1,15	180	—	2 r	1 r	5	1	6	0	100
	10	2 r	4 N	—	—	480	7 rs, 2 r	1 r	10	0	0	0	200

1) Under which the journal and bearing surfaces attain the condition corresponding, at most, to the coefficient 2 (see table 2).
2) Bearing ran with strong pressure on edges.
3) Numerous average lead inclusions only in one half of bearing.
4) Numerous average pores only in one half of bearing.
5) Measured in two perpendicular planes.

TABLE II. Valuation of the Bearing and Journal Conditions

Valuation number	Condition of bearing and journal* surfaces							Remarks
	Lead inclusions (bl)	Pores (p)	Scorings (r)	Scars (n)	Fractures (a)	Cracks (rs)	Scoured sections (fr)	
0	Surface perfectly smooth							
1	Few small	Few small	Traces	—	—	—	—	Perfect
2	Few medium	Few medium	Few medium	Few small	Few small	—	—	Acceptable
3	Few large	Few large	Several medium	Numerous small	Numerous small	—	—	Conditionally acceptable
4	Many small or medium	Many small or medium	Numerous medium	Some medium	Some medium	—	—	Necessary removal of surface imperfection
5	Several large	Several large	Few large	Numerous medium	Numerous medium	Few short	Traces	
6	Numerous small	Numerous small	Several large	Few large	Few large	Several short	Medium	Destroyed or unacceptable
7	Numerous medium	Numerous medium	Numerous large	Several large	Several large	Long	Few large	Removal or exchange
8	Numerous large	Numerous large	—	Numerous large	Numerous large (destroyed entirely)	—	Numerous large	

*Only scorings and scoured sections could be observed on the journals.

TABLE IV

Results of endurance test.

Bearing alloy	Bearing #	Bearing valuation # before test	Journal #	Bearing tolerance in ‰	Bearing pressure Static load kg/cm²	Dynamic load kg/cm²	Valuation # After test Bearing	Journal	Running time during endurance	Bearing wear mm·10⁻³		Journal wear mm·10⁻³	Running time during satisfactory bearing condition
20 I	922	0	14 V	0,98	250/190[2])	—	6 r, 2 n	5 r	80/17	99	130	2	56
20 I	924	0	4 N	1,07	—	250	5 rs, 2 r	2 r	100	28	15	0	0
20 III	1222	0	15 V	1,10	—	250	7 rs, 2 r	2 r	100	44	24	0	22
20 IV	822	0	14 V	1,02	—	250	2 r	2 r	96	12	10	0	>96
20 IV	823	0	8 E	1,02	250	—	2 r[4])	2 r	98	37	38	0	>98
30 I	937	6 bl	10 V	1,18	—	250/230[2])	7 rs, 6 p	1 r	11/2	8	3	0	0
30 II	333	7 bl	2 E	0,93	—	250/210[2])	7 p, 7 rs	2 r	15/43	83	15	0	0
30 IV	832	6 bl	8 E	1,03	—	250	6 p, 5 r[4])	0	95	61	35	0	0 (62)[3])
30 IV	833	6 bl	2 E	1,10	250/220[2])	—	6 p, 1 r[4])	1 r	24/72	98	98	0	0 (24)[3])
30 V	535	2 p	14 V	1,05	250	—	2 p, 2 r	2 r	102	38	40	0	>102
30 V	536	0	14 V	1,00	—	250	2 n, 2 r	2 r	106	23	12	0	>106
40 I	946	6 bl	10 V	1,17	—	250	6 p, 2 r	2 r	98	12	6	0	0 (>98)[3])
40 II	342	8 bl	11 V	0,93	—	250/210[2])	8 p, 1 r	2 r	28/23	62	46	0	0 (28)[3])
40 IV	846	6 p	9 N	1,13	—	250	8 a, 7 rs, 1 r	2 r	68	69	48	0	0

1) Journal and bearing surfaces, after the indicated running time, show injuries corresponding to the maximum coefficient 2.
2) The test pressure of 250 kg/cm^2 could no longer be attained after the indicated running time.
3) Figures in parentheses indicate running time not taking into account the positions of failure before the test.
4) The bearing surface is also roughened at some points.

TABLE V

Results after dry running test.

Bearing alloy	Bearing #	Journal #	Valuation # Before test Bearing	Journal	Bearing pressure kg/cm²	Pressure condition	Running time After stopping lubrication	Increase of temperature °C	No. of tests	Valuation # after test Bearing	Journal
20 I	924	4 N	5 rs, 2 r	2 r	250	dynamic	37″ to 11′13″	35° to 80°	8[1])	7 rs, 5 r, 4 n	2 r
20 I	927	3 N	7 rs, 2 r	1 r	250	static	3″ » 1′8″	5° » 40°	8[1])	7 rs, 2 r	2 r
20 III	1221	1 E	7 rs, 4 a	2 r	250	dynamic	4″ » 10′34″	5° » 50°	8[1])	7 rs, 5 r, 4 a	2 r
20 III	1222	15 V	7 rs, 2 r	2 r	250	dynamic	4′55″ » >10′	67° » >72°	8[1])	7 rs, 4 n, 2 r	2 r
20 IV	821	1 E	2 r	2 r	250	dynamic	4″ » 6′55″	5° » 27°	8[1])	5 r, 5 fr	5 r
20 IV	823	8 E	2 r	2 r	250	static	52″ » 2′48″	39° » 64°	5[2])	7 rs, 1 r	2 r
30 II	332	14 V	7 p, 7 rs	3 r	250	dynamic	7″ » 7′10″	6° » 58°	8[1])	7 p, 7 rs	3 r
30 V	533	2 E	7 rs, 2 r	2 r	250	static	3″ » 4′5″	6° » 38°	8[1])	7 rs, 2 r	2 r
30 V	535	14 V	2 p, 2 r	2 r	250	"	8″ » 21″	7° » 21°	8[1])	5 r, 2 p	5 r
30 V	536	14 V	2 n, 2 r	2 r	250	dynamic	6″ » 13′42″	7° » >77°	8[1])	2 n, 2 r	2 r
40 I	944	4 N	5 rs, 6 p, 4 a	2 r	250	dynamic	1′52″ » 12′31″	18° » 73°	8[1])	7 rs, 6 p, 4 a	5 r
40 I	946	10 V	6 p, 2 r	2 r	250	dynamic	7′50″	>80°	1[3])	8 n	2 r
40 II	341	8 E	8 p, 7 rs	2 r	250	dynamic	8″ » 6′24″	Apparatus destroyed	8[1])	8 p, 7 rs	4 r
40 IV	847	3 N	7 rs, 4 p	2 r	250	dynamic	7′29″ » >12′	54° to >70°	3[2])	7 rs, 4 p	2 r
Electrolytic copper	10	4 N	7 rs, 2 r	1 r	250	dynamic	34″ » 5′23″	26° « 42°	8[1])	7 rs, 2 r[4])	2 r

1) Further investigation discontinued.
2) Tests discontinued on account of disturbances in testing machine.
3) Further tests not possible on account of seizing of bearing.
4) Besides this, no measurable wear.

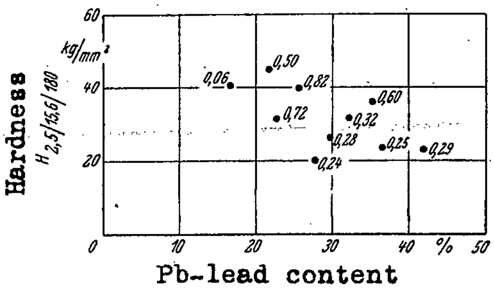


Figure 1.- Hardness of tested lead-bronze alloys as a function of the lead content. Numbers indicate impurities in percent.

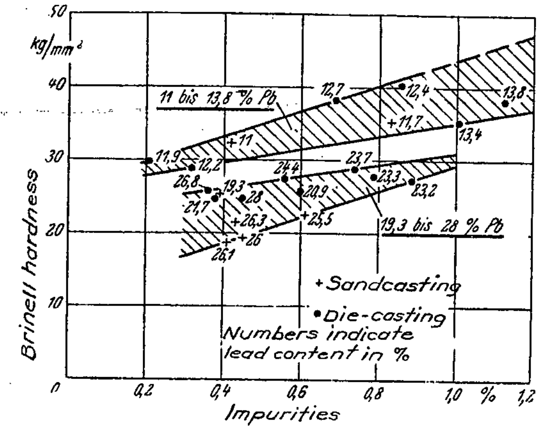


Figure 2.- Hardness of lead-bronze alloys as a function of impurities(as found by Hensel and Tichvinsky).

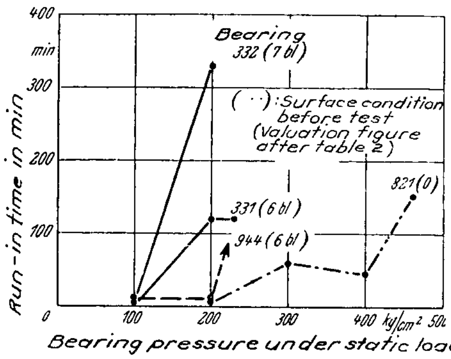


Figure 29 - Run-in times for different load steps under static load.

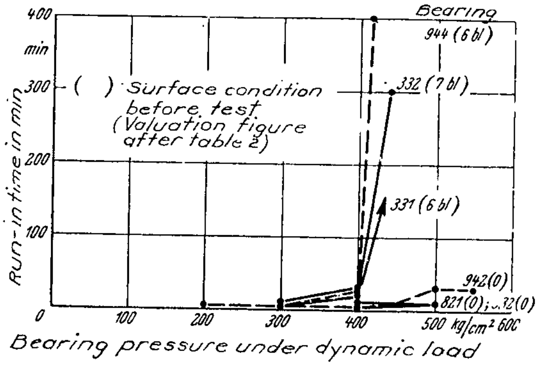


Figure 30.- Run-in times for different load steps under dynamic load.

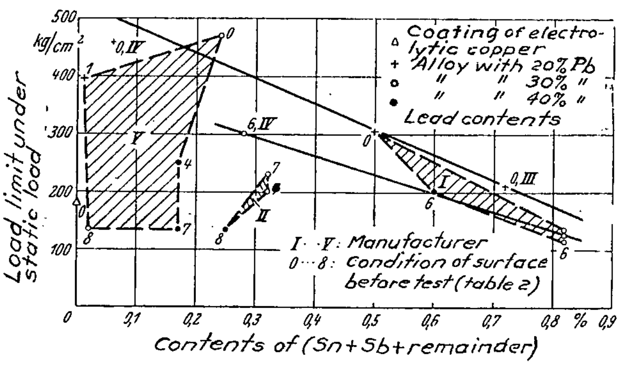


Figure 33.- Load limit as function of contents of impurities.

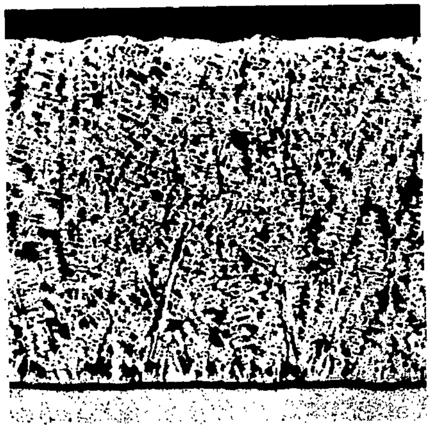


Figure 3.-Lead-bronze alloy 20 I (21.7% Pb); etched with weak acid. Magnification 50X.

Figure 4.- Lead-bronze alloy 20 III (22.6% Pb); etched with weak acid. Magnification 50X.

Figure 5.- Lead-bronze alloy 20 IV (16.8% Pb); etched with weak acid. Magnification 50X.

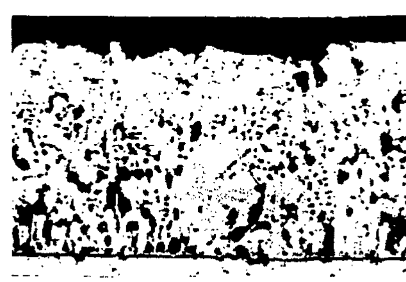


Figure 6.- Lead-bronze alloy 20 V 23.4% Pb); etched with weak acid. Magnification.50X. State after test run.

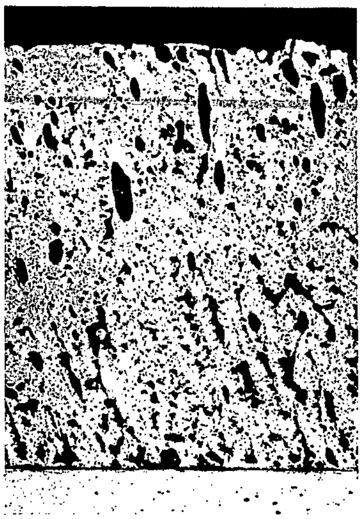


Figure 7. Alloy 30 I (25.6% Pb) Mag. 50X.

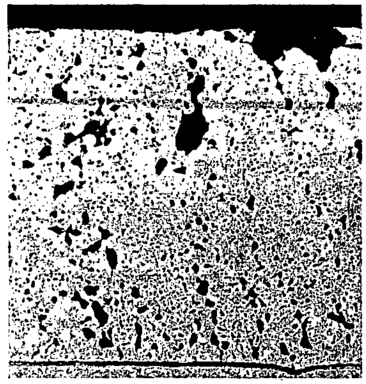


Figure 8. Alloy 30 II (32.3% Pb) Mag. 50X.

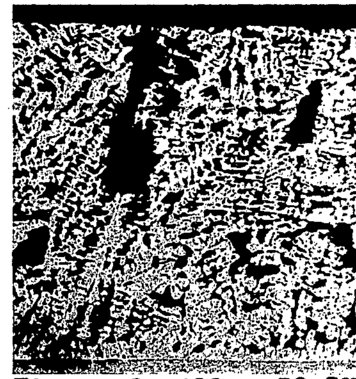


Figure 9. Alloy 30 IV (29.7% Pb) Mag. 50X.

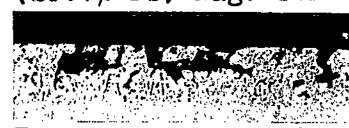


Figure 12. Mag. 10X.

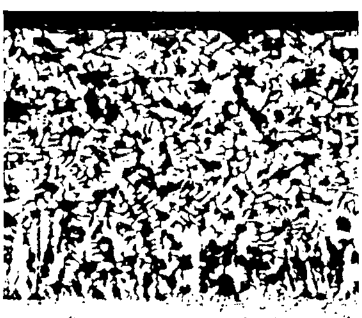


Figure 10. Alloy 30 V (27.8% Pb) Mag. 50X.

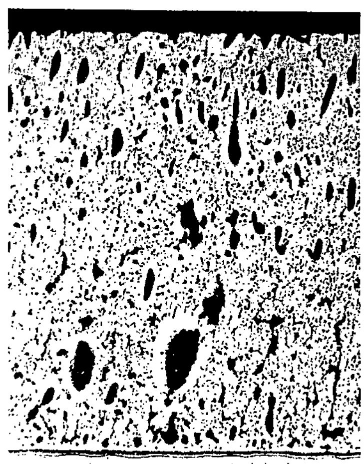


Figure 11. Alloy 40 I (35.2% Pb) Mag. 50X.

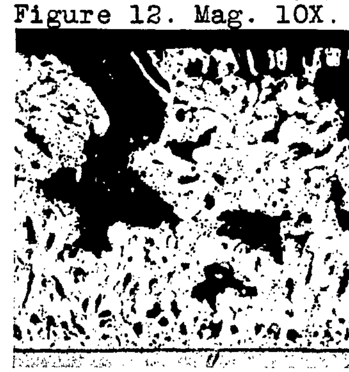


Figure 13. Mag. 50X. Alloy 40 II (38.3% Pb), for both figs.12,13.

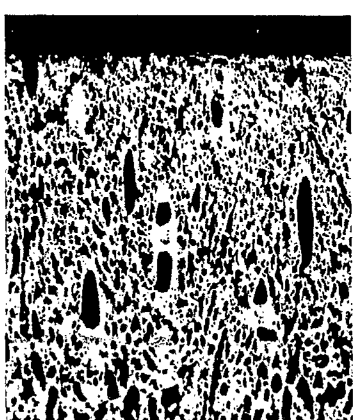
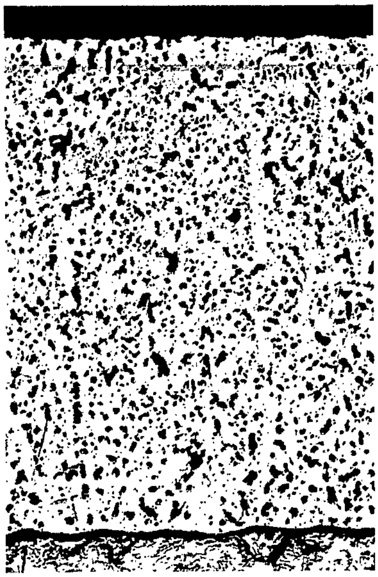


Figure 14. Alloy 40 IV (42.2% Pb) Mag. 50X.

Figure 15. Alloy 40 V (38.3% Pb) Mag. 50X. State after test run.

Figures 7 to 15.- Lead-bronze alloys etched with weak acid.



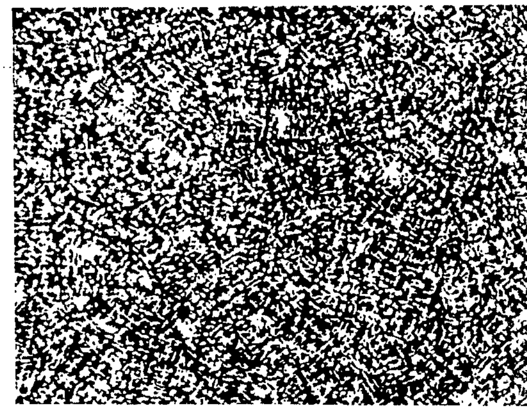


Figure 17.- Fine-dendritic structure of a foreign-made lead-bronze alloy with high lead content. Magnification 100X.

Figure 16.- Uniform and fine-globular lead distribution of a foreign-made lead bronze alloy.(70.70 Cu., 28.98 Pb.; .12 Ni.; .18 Fe;) Hardness $2.5/15.625/180 = 22 kg/mm^2$. Mag. 50X.

Figure 18.- Alloy 30 IV. Showing multitude of small lead inclusions after finishing operation.Magnification 2X.

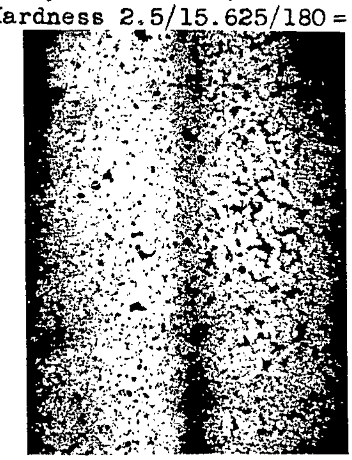


Figure 19.- Alloy 40 II. Showing numerous large lead inclusions after finishing operation.Magnification 2X.

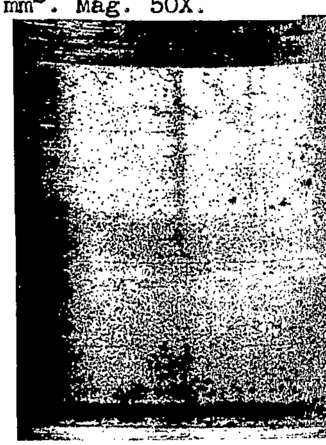


Figure 20.- Alloy 30 I (test bearing 932). Condition after test under static load up to $70 kg/cm^2$ side pressure,showing numerous small pores(instead of lead inclusion before the test). Notice on loaded side(near top of figure) small fracture and crack. Magnification 2X.

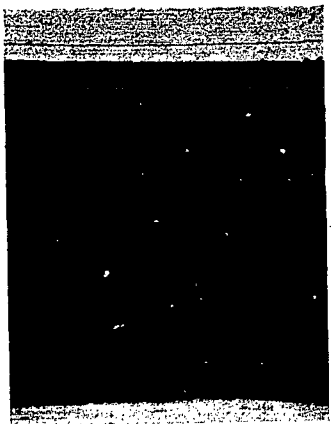


Fig.21.- Alloy 40 II (test bearing 342). State after 51 hr run under dynamic load with $p = 250(210)$ Kg/cm^2, showing medium and large pores (instead of lead inclusions before test). Also showing beginning of scoring. Magnification 2X.

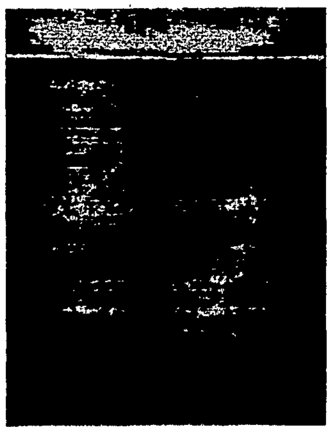


Fig.22.- Alloy 30 V (test bearing 531). State after test run under static load up to $p = 135$ Kg/cm^2, showing numerous large pores (already present before test) and light scoring. Mag. 2X.

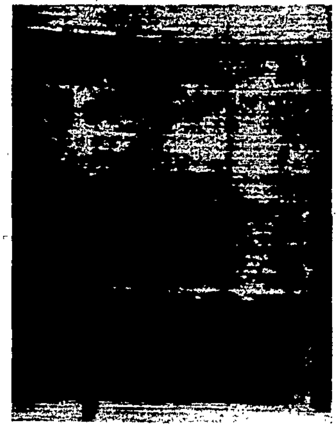


Fig.23.- Alloy 40 I (test bearing 942). State of bearing after test run under dynamic load up to $p = 550$ Kg/cm^2, showing light and some heavier scoring. Magnification 2X.

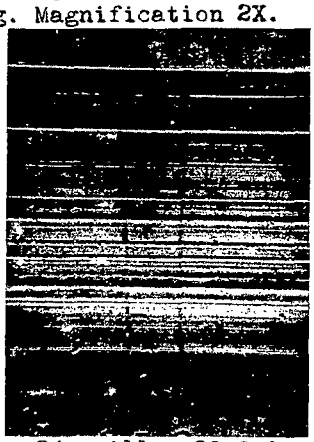


Fig.24.- Alloy 20 I (test bearing 922). State after 97 hr of testing under static load of $p = 250(190)$ Kg/cm^2. Test run showing a few light and six heavy scorings, also a few scars. (lines across center are caused by measuring tool). Magnification 2X.

Fig.25.- Alloy 40 I (test bearing 946). State after dry run under dynamic load with $p = 250$ Kg/cm^2, showing complete distruction of bearing. Lower part shows partial lead coating of surface. Magnification 2X.

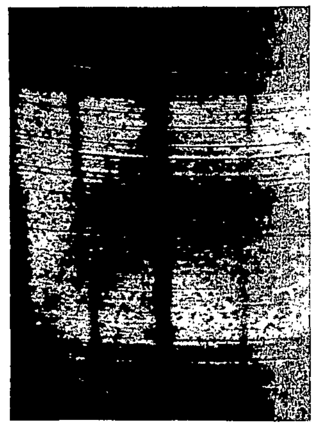


Fig.26.- Alloy 20 III (test bearing 1231). State of the unloaded zone after dry run under dynamic load with $p = 250$ Kg/cm^2, showing numerous fractures and scars, also a few light and heavy scorings. Magnification 2X.

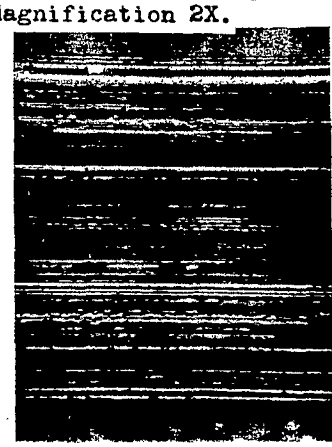


Fig.27.- Alloy 30 IV (test bearing 831). State after test under static load with $p = 300$ Kg/cm^2, showing complete destruction of bearing surface by heavy scoring and scouring. Magnification 2X.

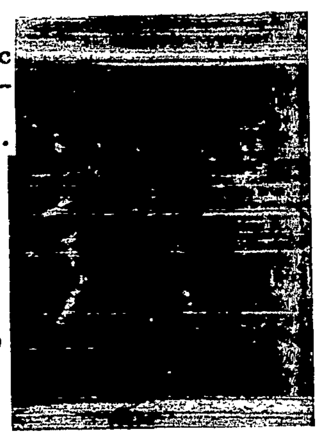


Fig.28.- Alloy 30 I (test bearing 937). State after 13 hours test under dynamic load with $p = 250(230)$ Kg/cm^2, showing numerous net-like cracks, also numerous pores and light scorings. Magnification 2X.

Figure 31.

Figure 32

Figures 31,32.- Alloy 30 I (test bearing 933). Shows crater-like enlargement of pores in the running surface in the end zone of lead segregations. (The micro-photographs show cuts parallel to the direction of rotation so that the cavities do not illustrate scorings in the surface.) In illustration 32, the cutting surface is made close to the entrance of the segregation into the running surface. Magnification 200X.

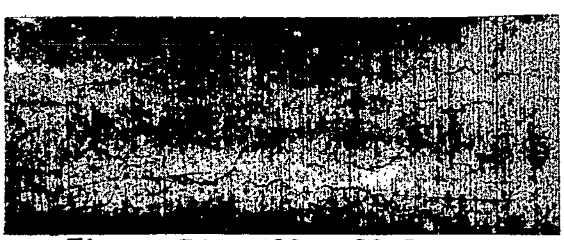


Figure 34.- Alloy 20 I.

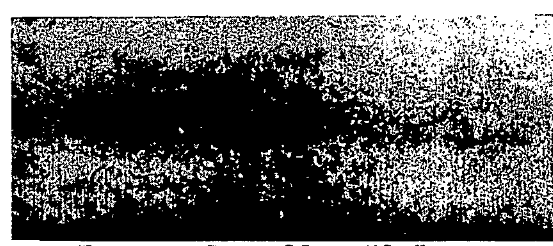


Figure 35.- Alloy 30 I.

Figures 34,35.- Crack forming of a finished bearing surface after two months storage. Magnification 2X.

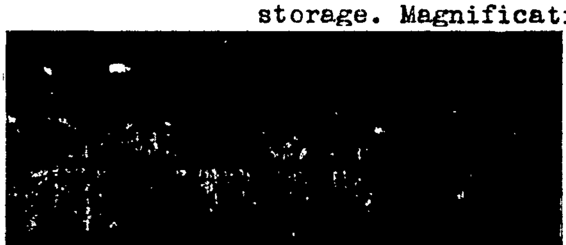


Figure 36.- Alloy 20 I.

Figure 37.- Alloy 30 I.

Figures 36,37.- Crack forming of a finished bearing surface after heating to 160° C . Magnification 7.5X.

Figure 38.

Figure 39.

Figures 38,39.- Cracks within the alloys illustrated in figures 34 and 35 made of alloys 20 I and 30 I. Magnification 50X.

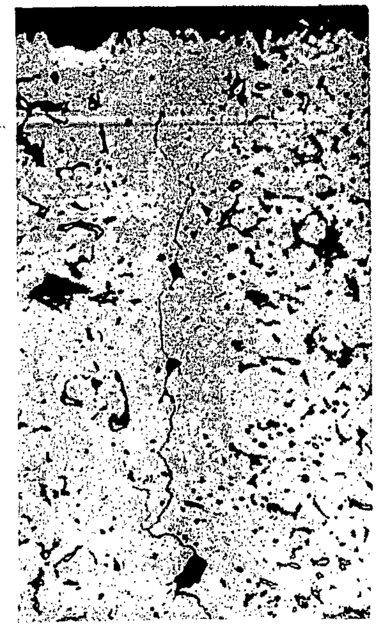


Figure 40.- Crack within the tested bearing material made of alloy 30 I (bearing 933). Magnification 200X.

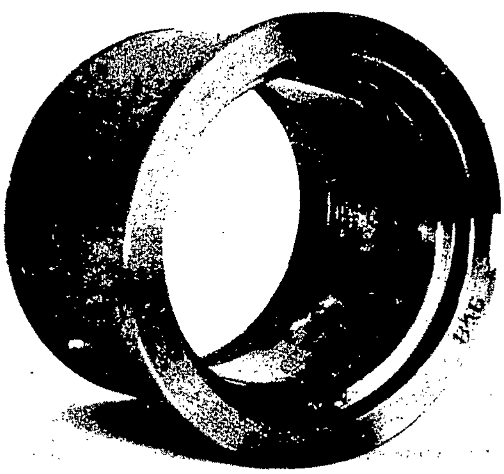


Figure 41.- Cracked surface of bearing 846, made of alloy 40 IV (42% Pb,28% Fe). State after 68 hours of dynamic test at $p = 250 Kg/cm^2$.

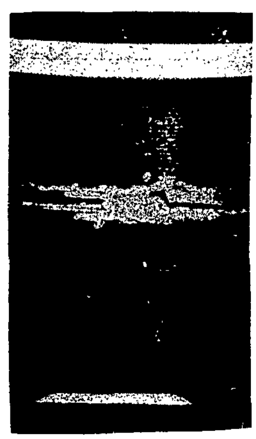


Figure 42.- Local lead collection in the running surface created by a foreign body during an endurance run. (The foreign part is visible next to the damaged part of the surface.)